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Effect of Different Drill Bits on Delamination in Drilling Composite Materials

Haşim PIHTILI[1*]
[1] Department of Mechanical Engineering, Firat University, Engineering Faculty, 23279 Elazığ, Turkey
[*1] hpihtili@firat.edu.tr

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Abstract: The most important problem of composite materials, which have been started to be used in every field of technology, is the ability to perform machining operations such as drilling and cutting. In this respect, in this experimental study, its performance in drilling different composite materials with different reinforcements and thicknesses with drills of different types and different diameters was investigated. Three different types of drills were used in drilling operations, namely HSS, TIN and Carbide. Reinforced composites of different types and properties were used as materials. As a result of the drilling processes, the surface roughness of the drilled surface, drilling performance, hole quality and different cutting parameters were examined depending on the rotation and feed rate. The same drilling conditions were applied for each composite material. All result values obtained were transferred to graphs and tables. In addition, photographs of all samples were taken under Scanning electron microscopy (SEM) and the surface roughness of these photographs was examined.

Key words: Drill Bits, Drilling, Reinforced Composites, Roughness

Kompozit Malzemelerin Delinmesinde Farklı Matkap Uçlarının Delaminasyona Etkisi

Öz: Teknolojinin her alanında kullanılmaya başlanan kompozit malzemelerin en önemli problemi, delme, kesme gibi talaşlı işlemin gerçekleştirilebilme durumudur. Bu bakımdan, bu deneysel çalışmada, değişik tür ve farklı çaplara sahip olan matkaplarla, değişik takviyeli ve kalınlıktaki farklı kompozit malzemelerin delinmesindeki performansı incelendi. Delme işlemlerinde, HSS, TIN ve Karbür olmak üzere üç çeşit değişik matkap kullanıldı. Malzeme olarak değişik tip ve özelliklerdeki takviyeli kompozitler kullanıldı. Yapılan delme işlemlerinin sonucunda, devir ve ilerleme hızına bağlı olarak, delinmiş yüzeydeki yüzey pürüzlülüğü, delme performansı ile delik kalitesi ve değişik kesme parametreleri incelendi. Her bir kompozit malzeme için aynı delme şartları uygulandı. Hem matkap hem de kompozit malzemede meydana gelen delaminasyon incelendi. Elde edilen tüm sonuç değerleri, grafiklere ve tablolara aktarıldı. Ayrıca, tüm numunelerin fotoğrafları taramalı elektron mikroskobu (SEM) altında çekildi ve bu fotoğraflardaki yüzey pürüzlülük durumu incelendi.

Anahtar kelimeler: Matkap ucu, Delme, Takviyeli Kompozitler, Yüzey pürüzlülüğü

1. Introduction

In today's technology, the use of composite materials in all areas is increasing day by day. Especially, it has become an indispensable material in the aerospace and aircraft industry, automotive industry, and sports and marine materials. Composite materials have numerous characteristics such as lightness, rigidity, heat resistance, high strength, and good abrasion resistance. However, despite the manufacturing industry has developed modern machining methods, traditional drilling method is still the most widely used machining process due to the reasons such as its economy and simple applicability. Fibre reinforced composites are widely recognized for their superior mechanical properties and advantages for applications in aerospace, defence and transportation sec tors (Hocheng, 2005). However, composite materials have char-act eristics which drive their machining behaviour, therefore, the mechanisms involved while cutting composite materials have been regarded as considerably distinct from those observed when cutting homogeneous materials (Hocheng,2006).

Carbon fiber-reinforced composites are well recognized for their superior mechanical properties and are widely used in aerospace, defense and transportation applications. Composite materials possess peculiar characteristics during machining. The reference of drilling of fiber-reinforced plastics reports that the quality of the machined parts is strongly dependent on drilling parameter (W. Koenig,1985), (R. Komanduri,1991). Numerous studies have examined the delamination in drilling (G. Caprino,1995), (J.A. Miller,1984), (K. Sakuma,1984), (F. Veniali,1995), (W. Koenig,1984). In Fig. 1, the center of the circular plate is loaded by a twist drill of diameter d. FA is the thrust force, X is the displacement, H is the workpiece thickness, h is the uncut depth under tool, 2b is the diameter of pilot hole, and a is the radius of existing delamination, (C.C.Tsao, H.Hocheng,2003).
Fig.2 shows the delamination damage at the drill entrance and exit of a laminate composite material (Koenig,1984). When the studies on the processing of composites are examined, mostly the metal matrix composites (MMC) are

encountered. Pihtili and Canpolat, in the study, drilling performance and cutting parameters with holes having different qualities, drill kinds, and drill diameters are examined in different composite materials. As a result of the drilling operations, it is found that as rotation and progress speed increases, surface roughness on the processed surface increases as well. Better results in terms of surface roughness are obtained with small-scaled drills (Pihtili,2009). Schafer, as a whole, it is observed in the drilling tests performed on MMC that when conventional high speed steel (HSS) drills are used, tool wear is high and the surface roughness of the hole is weak (Schaefer,1969). Chamber, In the study of Chamber and Stepfens, MMCs are processed in the lathe by using different cutting tools. It was observed that Polly Crystal Diamond(PCD)drills have high wearing resistance, longer tool life, and the best surface roughness values are obtained when the machining process is performed by using these drills (Chamber,1991). Joshi et al. analyzed the wearing of the carbide tool and chips that are ruptured during the machining of the metal matrix composite on the lathe. In the current study, chips with a larger diameter were obtained by decreasing the angle of shear (Joshi,1999). In the study of El-Gallab and Sklad, the surface roughness of the metal matrix with machined particles is emphasized. They investigated the effect of cutting parameters on surface roughness by performing dry turning tests at different cutting speeds, different feed rates, and different cutting depths (El-Gallab,1998). Lin et al. examined the forms of chips at different cutting rates of aluminum-matrix composite. In the present study, the decrease in brittleness via the addition of SiC particles to the Al alloy caused semi-continuous chips to be formed during the machining of MMCs (Lin,1998). S.Arul et al. examined the effect of vibrated drilling on the quality of the holes in the polymeric composites. Especially, they emphasized on a new drilling method by applying low frequency and high voltage on the part in the direction of the feed during drilling. As a result of literature reviews, studies on the machining of composites are generally focused on the drill life. However, it has been observed that there are no further examinations conducted on the material after machining. The effects of feed rate, number of cycles, type of drill, and the drill diameter on the surface roughness of the workpiece are examined while drilling the composite material (Arul, 2006).Senol B. investigated the drillability of CuSn10 and GGG40 MMCs having different reinforcement rates (10%–20%–30%–40%) under dry cutting conditions with carbide drill. As the reinforcement ratio is increased, the Stronsiyum (SR)is also increased, whereas the feed force is decreased. During cutting process, GGG 40 metallic chips act as fillers with different hardness values than the matrix (Şenol,2021Kosedag,E.,et all.he low-velocity impact behavior of SiC nanoparticle-glass fiber-reinforced polymer matrix composites (PMC) in terms of different weight fraction of nanoparticle, artificial aging time, and impact energy was investigated in this study (2021). Kosedag,M.,Aydin,and Ekici, in another study was to reveal the effect of stacking sequence (SS), metal volume fraction (MVF), and number of layers on ballistic resistance in fiber metal laminates (FMLs). Four types of FMLs in different sequences and MVF (25% and 50%) were produced with hot press and vacuum(2021).

The aim of this study, the surface roughness of the composite materials is examined depending on the effect of drill type, diameter of the drill, rotational speed, and feed rate regarding the machinability of various composite materials in the drilling process.

2. Model of delamination analysis

During drilling-induced delamination, the drill movement of distance dX is associated with the work done by the thrust force FA, which is used to deflect the plate, as well as to propagate the interlaminar crack. The energy balance equation gives

$$G_{IC}\,.dA = F_A.dX.dU \tag{1}$$

Where dU is the infinitesimal strain energy, dA is the increase in the area of the delamination crack, and G_{IC} is the critical crack propagation energy per unit area in mode I. The value of G_{IC} is assumed a constant to be a mild function of strain rate by Saghizadeh and Dhahran, (1986). Fig. 1 depicts the schematics of delamination with a pre-drilled central hole. The diameter of the pilot hole is selected equal to the chisel length of drill, in order to eliminate the disadvantage of the chisel-induced thrust force and avoids the threat of creating large delamination by large pre-drilled hole. In Fig. 1, the center of the circular plate is loaded by a twist drill of diameter d. FA is the thrust force, X is the displacement, H is the workpiece thickness, h is the uncut depth under tool, 2b is the diameter of pilot hole, and a is the radius of existing delamination, (C.C.Tsao, H.Hocheng,2003).

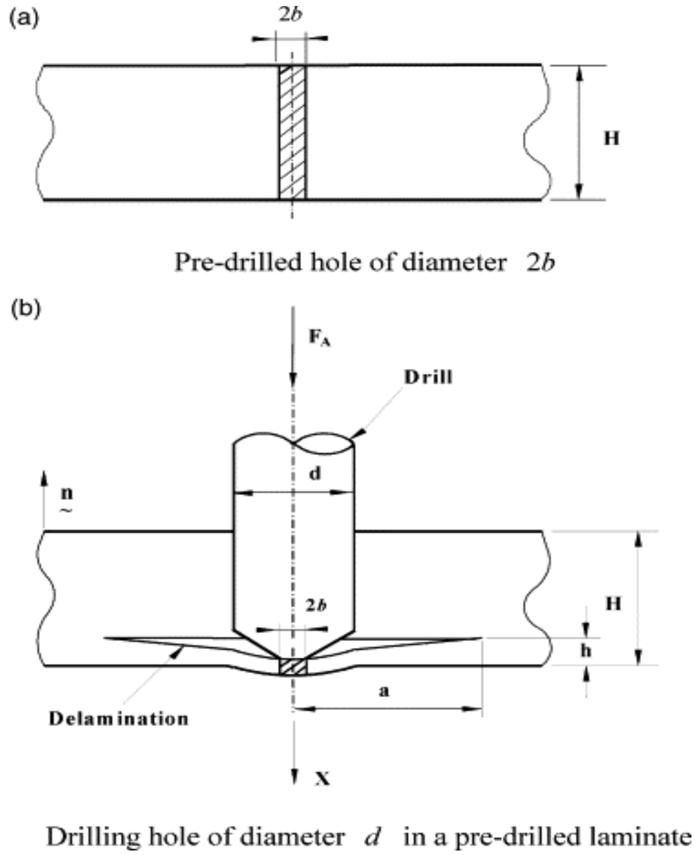

Figure 1. Circular plate model for delamination analysis of a pre-drilled specimen [11]

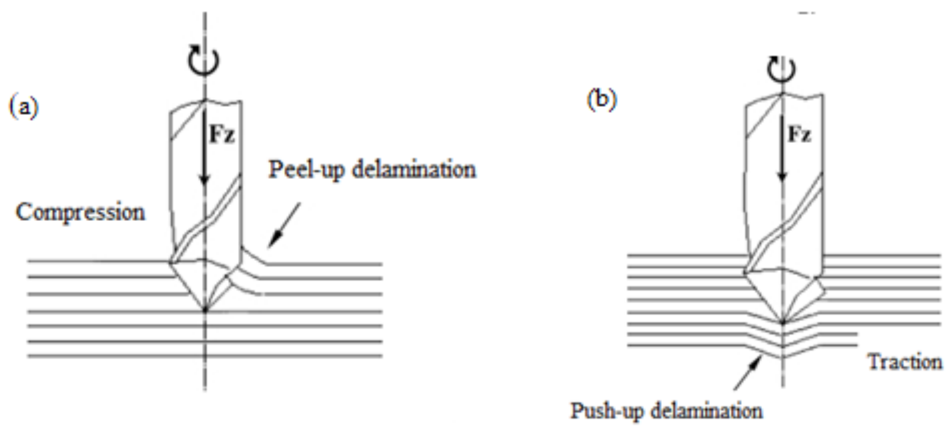

Figure 2. Delamination at the tool entry (a) and exit (b) when drilling Composite laminate [3]

3 . Materials and Method

CYCOM 7701 and CYCOM 7714 epoxy resins were used as matrix material in the tests. These resins are self-destructive resins that resist dissolving, designed specifically for use in structural laminates and honeycomb core sandwich panels for aircraft. Formulated for autoclaving or process printing. It can be absorbed into all suitable structures by the dissolution process. They are generally applied on aramid and glass fiber. ISOVAL11 is made of glass fabric impregnated with a heat resistant version of the epoxy system. The layers show excellent thermal and chemical resistance as well as mechanical strength at high temperatures (Pihtili, 2009). Plastic matrix composites produced in different forms are used in the tests to be used in the drilling process. Materials were produced from various companies as semi-finished and finished products. Semi-finished materials are made ready for use in tests as finished products by going through various processes. Table 1 shows the composite materials used in the tests. Semi-finished materials in the size of 21x29.7 cm, which were previously supplied from private companies, were cut to certain dimensions for perforation. Afterwards, the prepared samples were kept in a 10-ton press at 80 degrees for 2 minutes, and then kept in a 5 tons of hot press at 80 degrees for 15 minutes, and 80x110 mm composite materials were obtained. In order for all the produced materials to turn into a homogeneous structure, they were stored in the refrigerator for 20-30 minutes after the hot pressing process and allowed to cool rapidly

Table 1 The composite materials used in experiments.

Material	**Characteristics**	**Texture**	**Thickness** (mm)	**status**
CYCOM7701-A	Epoksi/E-glass fiber	170 g/m^2	0.1	Semi-finished product
CYCOM7701-B	Epoksi/E-glass fiber	485 g/m^2	0.25	Semi-finished product
CYCOM7701-C	Epoksi/E-glass fiber	610 g/m^2	0.35	Semi-finished product
CYCOM7714-A	Epoksi/Kevlar 49	370 g/m^2	0.27	Semi-finished product
CYCOM7714-B	Epoksi/Kevlar 49	142 g/m^2	0.105	Semi-finished product
ISOVAL11-A	Epoksi/E-glass fiber	0.2 g/cm^3	2	Finished materials
ISOVAL11-B	Epoksi/E-glass fiber	0.2 g/cm^3	3.5	Finished materials
ISOVAL11-C	Epoksi/E-glass fiber	0.2 g/cm^3	5	Finished materials
ISOVAL11-D	Epoksi/E-glass fiber	0.2 g/cm^3	7	Finished materials
ISOVAL11-E	Epoksi/E-glass fiber	0.2 g/cm^3	10	Finished materials

ISOVAL11-F	Epoksi/E-glass fiber	0.2 g/cm^3	14	Finished materials

3.1 Drilling Processes

In order to achieve optimum results in the drilling process, the maximum size of the drilling length was chosen as 15 mm in order to comply with the requirement that it should be three times or less than three times of the hole diameter in the literature. Coolant is not used to reduce the possible heat shock in the tools during the test (Durante, 1997). During the drilling processes, the experiments are conducted via dry drilling the Stanke import brand radial drilling machine, which operates between 20 rpm and 2000 rpm, and has a feed range of 0.056 mm/rev and 2.5 mm/rev.

3.2 Cutting Tools

In the tests, N-type drills with a helix angle of 30°±3 and a point angle of 118° are used. A new drill is used in every test (Fig. 3).In drilling operations, 3 different types of drills, HSS, TIN and Carbide, with the diameter of 5 mm are used. Experiments are conducted with dry drilling at cutting speed of 125 rpm and progresses of feed rate 0.056 mm/rev.

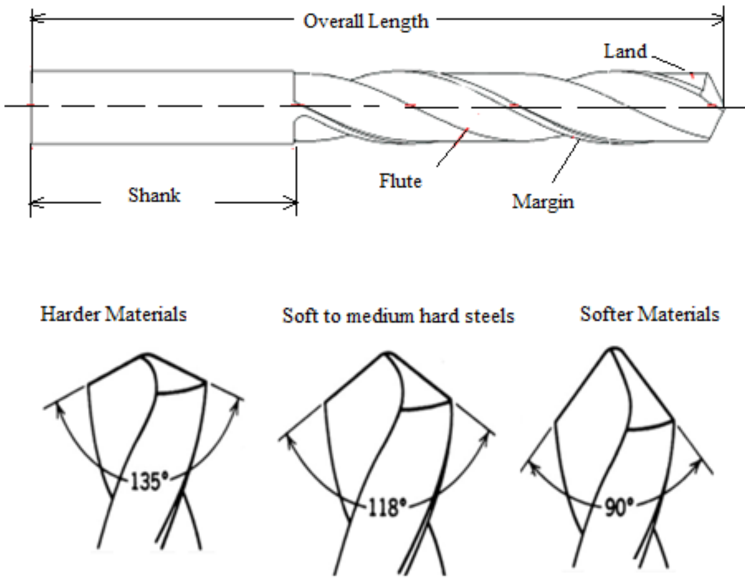

Figure 3. Drill type used in the Drilling Process

After the type of drill is selected, process parameters are specified. These are feed rate drilling speeds, and coolant, if used. Progress is expressed in s mm/rev or mm/min, and it is the distance the drill travels in the axial direction in one revolution. For a sufficient drilling and economical tool life, it is necessary to use the highest feed rate possible. The drilling speed gives the circumferential or surface speed of the drill in m/min. The correlation between the rotating speed of the drill and the drilling speed is given below.

$$V = \frac{\pi \cdot d \cdot n}{1000} \tag{2}$$

$$n = \frac{1000 \cdot V}{\pi \cdot d} \quad (3)$$

Where;

V = drilling speed m/min.

d = diameter of the drill

n= rotating speed of the drill rev/min.

Ra values were calculated with the following formula:

Ra = 0.58 – 0.013 x KM + 0.273 - snd + 0.276 x MM (micron) (4)

where;

KM is the composite material, MM is the drill material, and snd =rpm.

In addition,

TW=3, HSS=2, and carbide=1 values were considered.

These values are constant values used in the solution of Ra.

4. Transferring and Analyzing the Test Results to Graphics

4.1 Examination of Surface Roughness

The composite samples, which are drilled, were then sheared right in the middle parallel to the hole axis. Surface roughness of the materials around the hole is measured by the Mitutoyo Suftest-211 device in order to examine the drilling performance depending on different drilling parameters. Surface roughness is determined by taking three measurements for each of Ra and Ry values from every surface and taking their averages. Table 2 shows the test parameters and surface roughness values of the workpiece obtained as a result of the tests performed under different drilling conditions (Pihtili,2009).

4.2 CYCOM7714 Composite Sample Plates used in Drilling

Kevlar 49 is used as the reinforcement material (Fig.4). A total of 8 drilling are applied to CYCOM7714 Composite sample plates. Overheating occurred in the drill during the material drilling process. It is determined that the material is torn and holes are found at the inlet and outlet of the material, however, the surface roughness in the intermediate layer is lower, especially the Ry values are much lower than the fiber glass reinforcement. Good results are especially obtained in carbide tools in terms of surface roughness. It is observed that the diameter of the drill had no effect on the surface roughness, and some burns are observed on the surface that are caused by heat generated in the material during drilling.

Table 2. Test parameters and results.

Material	**Drill Type**	**Average surface roughness Ra (μ)**	**Maximum surface roughness Ry (μ)**
CYCOM7701-C	Carbide	1,13	5,1
CYCOM7701-C	TiN	2,27	6,8
CYCOM7701-C	HSS	3,01	6,1
CYCOM7714-A	Carbide	0,83	3,8
CYCOM7714-A	TiN	1,47	3,8
CYCOM7714-A	HSS	1,71	5,1
CYCOM7714-B	Carbide	0,64	2,1
CYCOM7714-B	TiN	1,11	3,7
CYCOM7714-B	HSS	1,84	2,9
ISOVAL11-A	Carbide	1,02	5,1
ISOVAL11-A	TiN	1,44	5,7
ISOVAL11-A	HSS	1,37	6,9

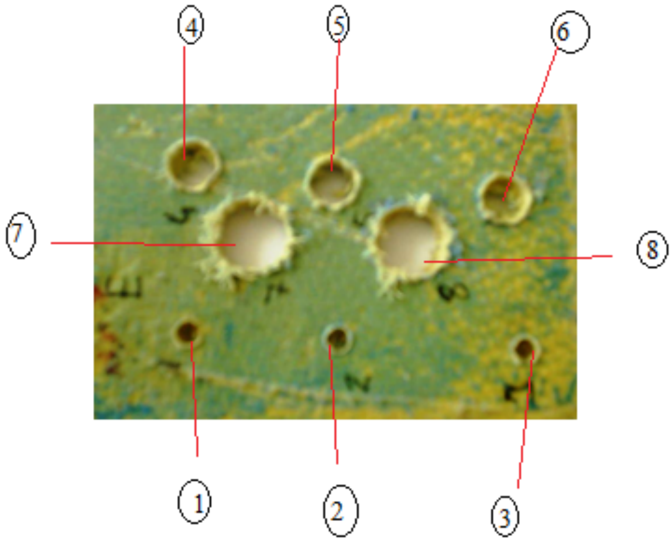

Figure 4. CYCOM7714-A Composite materials used in experiments.(8 holes of different diameter)

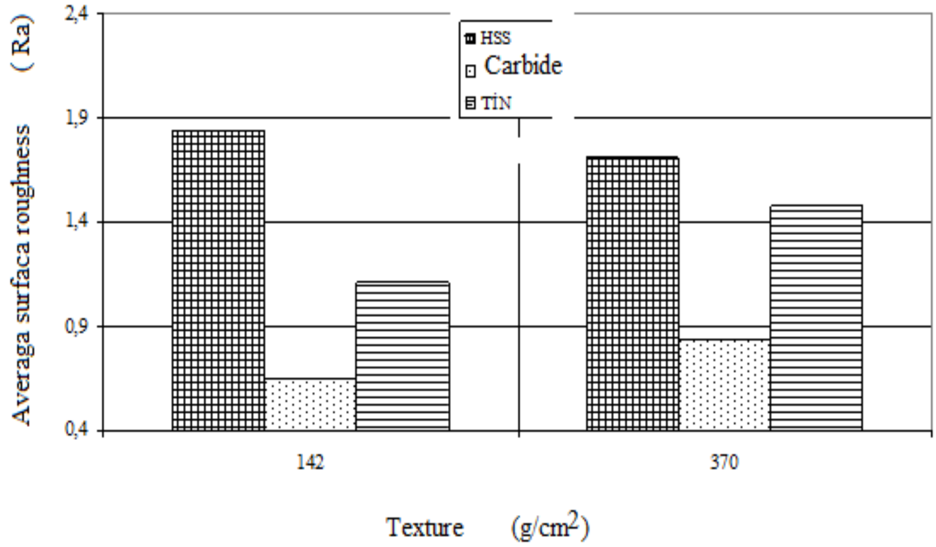

Figure 5. Variation of the average surface roughness with the weave density of the CYCOM7714 epoxy / Kevlar49 composite (s=0.056 mm/rev, n=125 rpm, d=5 mm)

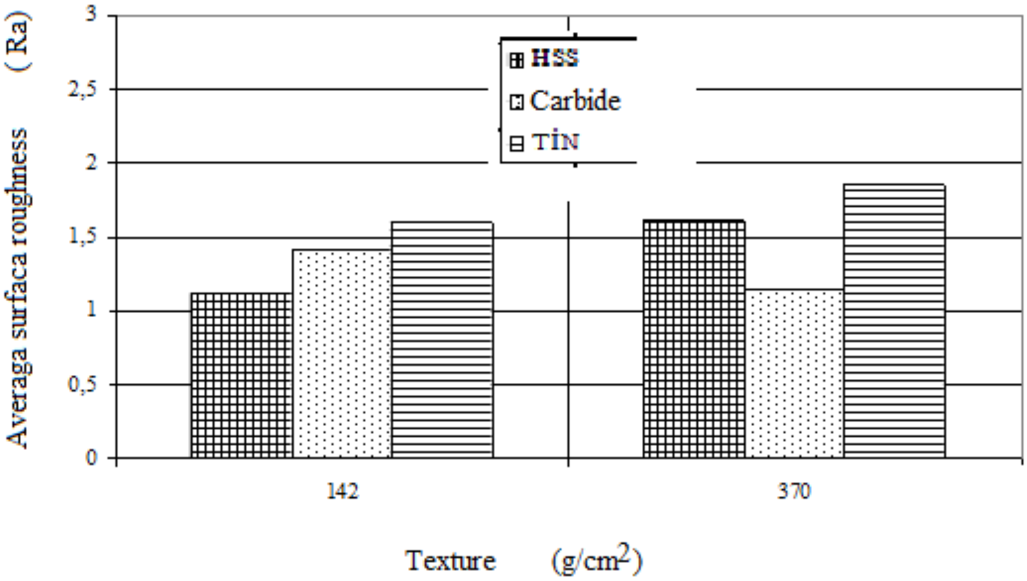

Figure 6. Variation of the average surface roughness with the weave density of the CYCOM7714 epoxy / Kevlar49 composite (s=0.112 mm/rev, n=250 rpm, d=10 mm)

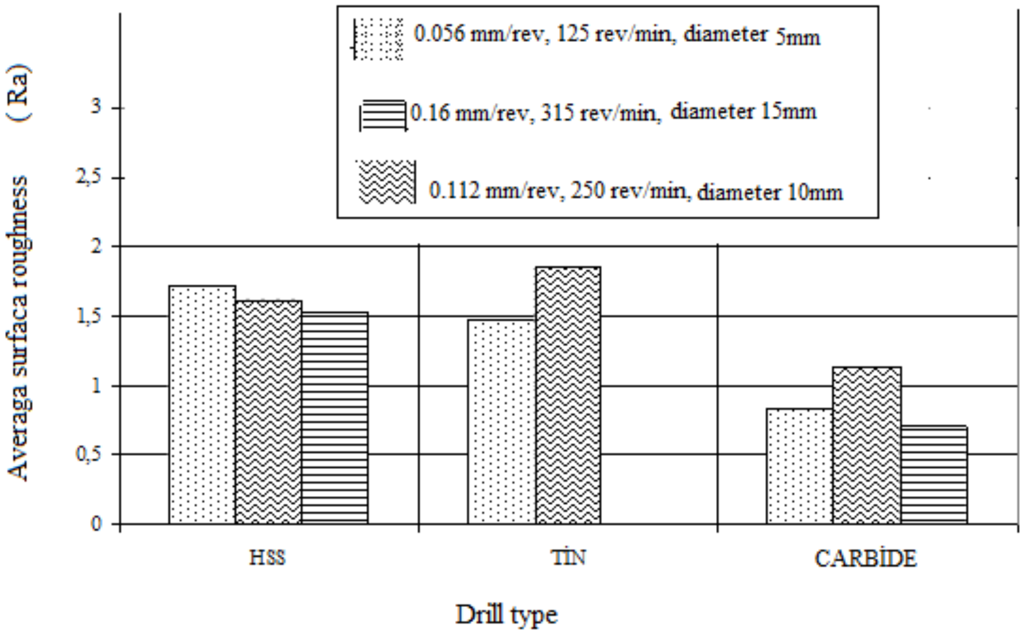

Figure 7. The change in drill material and the average surface roughness for CYCOM7714 Epoxy/ Kevlar49 fiber composite (texture densit 485 g/m^2, semi-finished material thickness 0.25 mm)

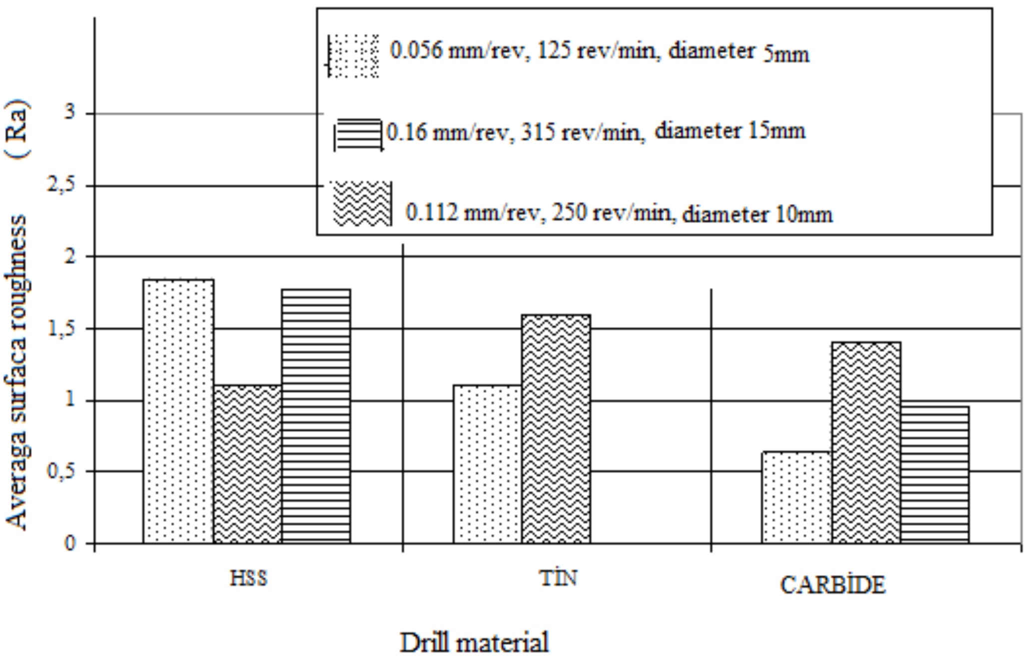

Figure 8. The change in drill material and the average surface roughness for CYCOM7714 Epoxy/ Kevlar49 fiber composite (texture densit 142 g/m^2, semi-finished material thickness 0.15 mm)

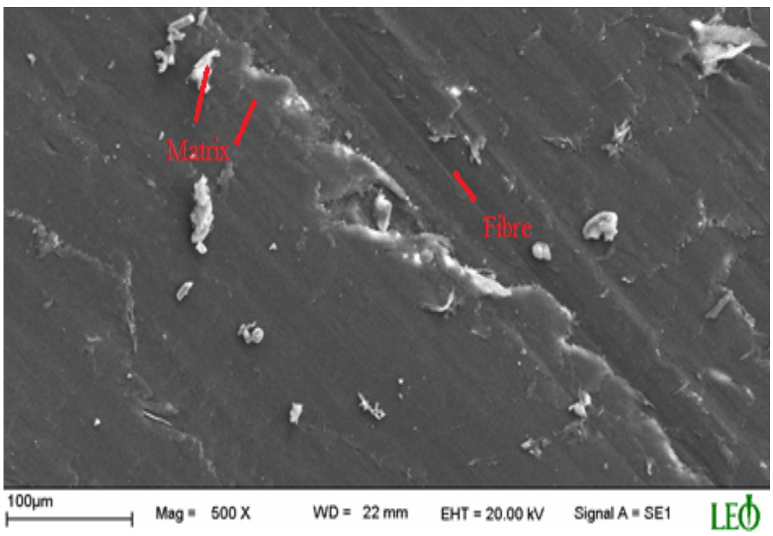

Figure 9. 500x enlarged SEM photo of middle point of hole section for CYCOM7714 Epoxy/ Kevlar49 fiber composite drilled with HSS drill (texture density 142 g/m^2, semi-finished material thickness 0.105 mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

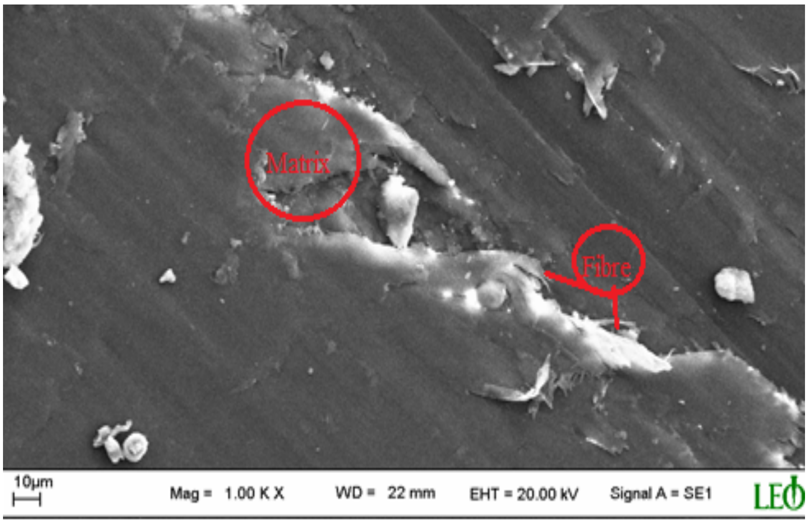

Figure 10. 1000x enlarged SEM photo of middle point of hole section for CYCOM7714 Epoxy/ Kevlar49 fiber composite drilled with HSS drill (texture density 142 g/m^2, semi-finished material thickness 0.105 mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

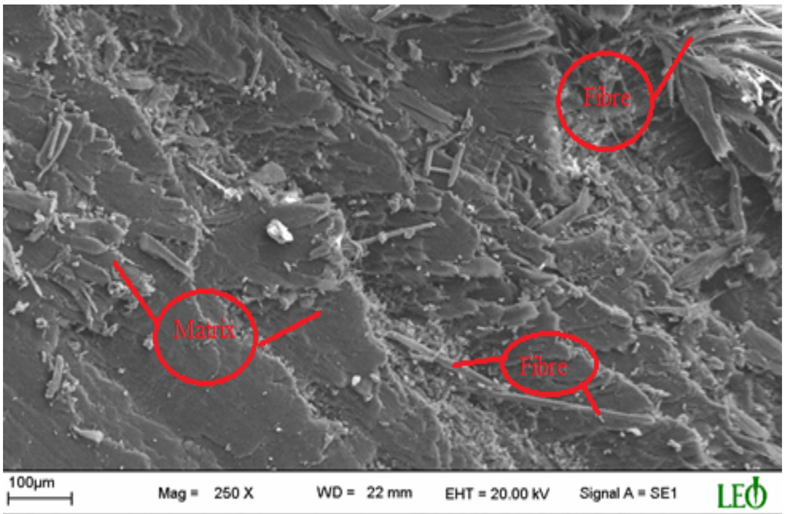

Figure 11. 250x enlarged SEM photo of middle point of hole section for CYCOM7714 Epoxy/ Kevlar49 fiber composite drilled with HSS drill (texture density 142 g/m^2, semi-finished material thickness 0.105 mm,s=0.16 mm/rev, n=315 rpm, d=15 mm)

4.3 CYCOM7701 Composite Plate Sample used in Drilling

Figure 12 shows the CYCOM7701 series type composite layer material. 8 drilling processes are conducted in total Carbide, TiN and HSS drills are used for the drilling processes having diameters of 5mm and 10 mm. It is observed that more sensitive surface was obtained in the drilling processes performed by using carbide drills at the same revolution and progress, and the same situation was also present in the drills having diameters of 10 mm and 15 mm. Figure 13 and 14 show the maximum surface roughness values obtained as a result of drilling.

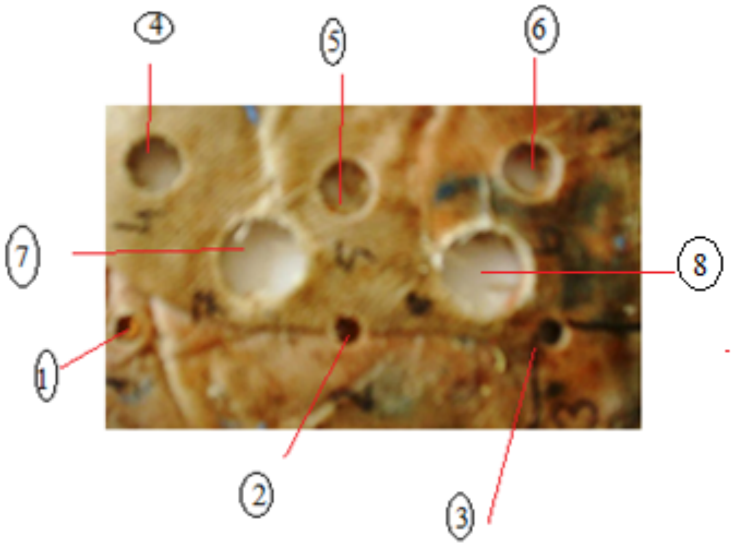

Figure 12. CYCOM7701-C Composite materials used in experiments

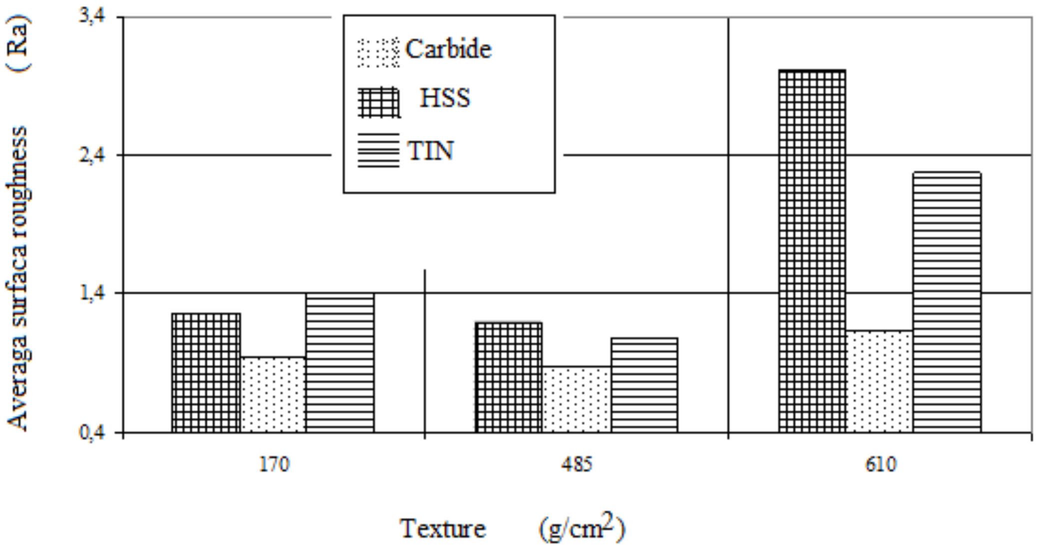

Figure 13. The change in Texture (g/cm^2) and the average surface roughness for CYCOM7701 Epoxy/E-glass fiber composite (s=0.056 mm/rev, n=125 rpm, d=5 mm)

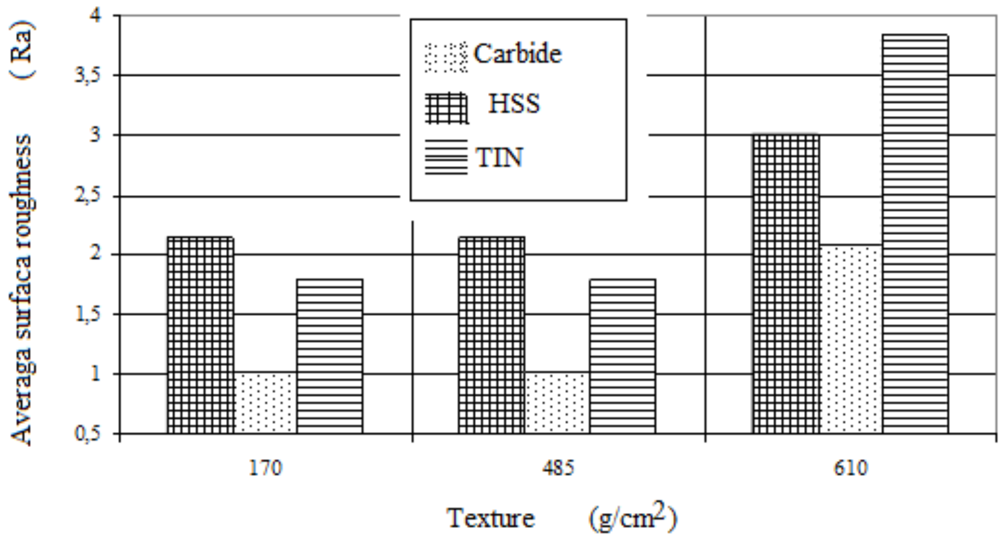

Figure 14. The change in Texture (g/cm^2) and the average surface roughness for CYCOM7701 Epoxy/E-glass fiber composite (s=0.112 mm/rev, n=250 rev/min, d=10 mm)

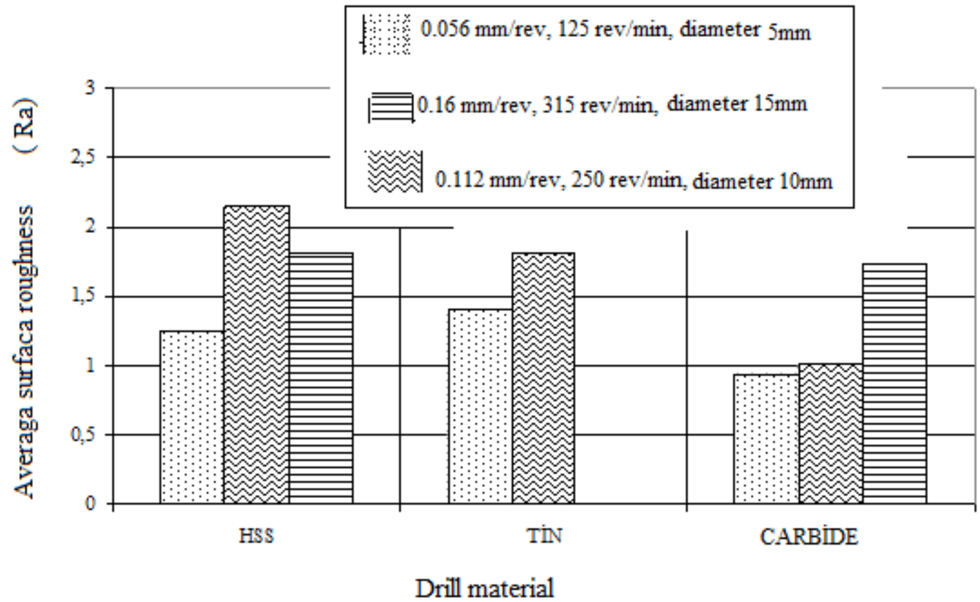

Figure 15. The change in Texture (g/cm^2) and the average surface roughness for CYCOM7701 Epoxy/E-glass fiber composite (texture density 170 g/m^2, semi-finished material thickness 0.1mm).

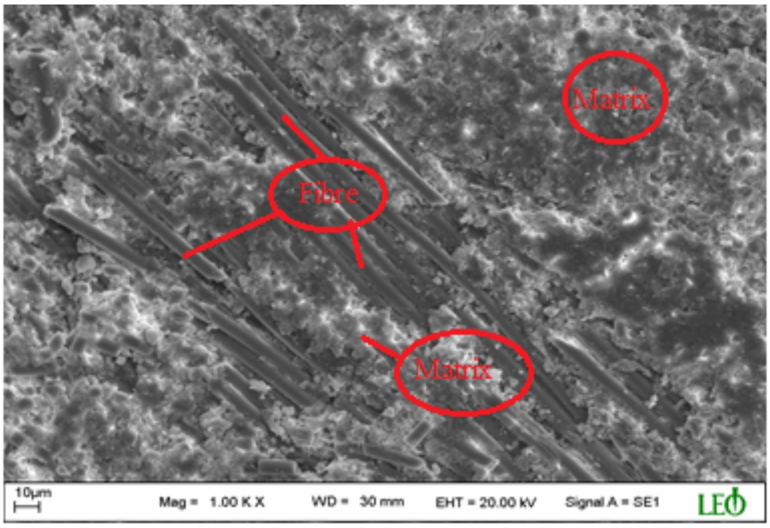

Figure 16. 1000x enlarged SEM photo of middle point of hole section for CYCOM7701 Epoxy/ E-glass fiber composite drilled with HSS drill (texture density 485 g/m^2, semi-finished material thickness 0.25 mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

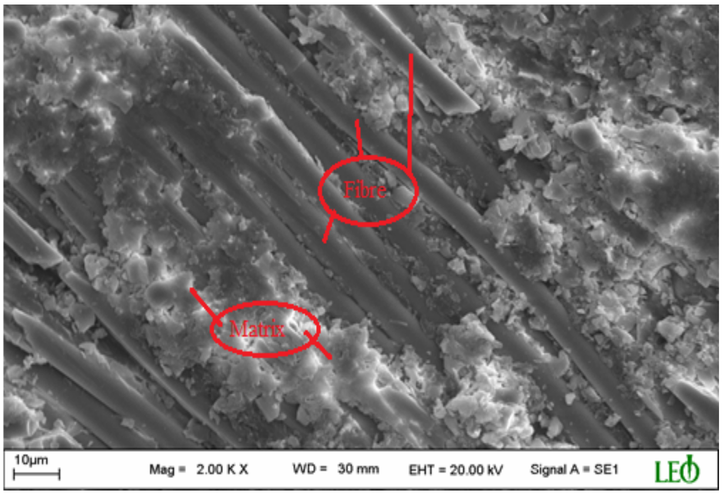

Figure 17. 2000x enlarged SEM photo of middle point of hole section for CYCOM7701 Epoxy/ E-glass fiber composite drilled with HSS drill (texture density 485 g/m^2, semi-finished material thickness 0.25 mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

4.4 ISOVAL11 Composite Plate used in Drilling

Figure 18 shows the ISOVAL11 series type composite material. A total of 8 drilling processes are applied with the ISOVAL11 material having a thickness of 3.5 mm. It is observed that more sensitive surface is obtained in the drilling processes performed by using carbide drills at the same revolution and progress, and the same situation was also present in the drills having diameters of 10 mm and 15 mm. It is observed that there is little heating on the tool, where the chips are formed in the powder form. Ry value is found to be high in the holes with a diameter of 15 mm.

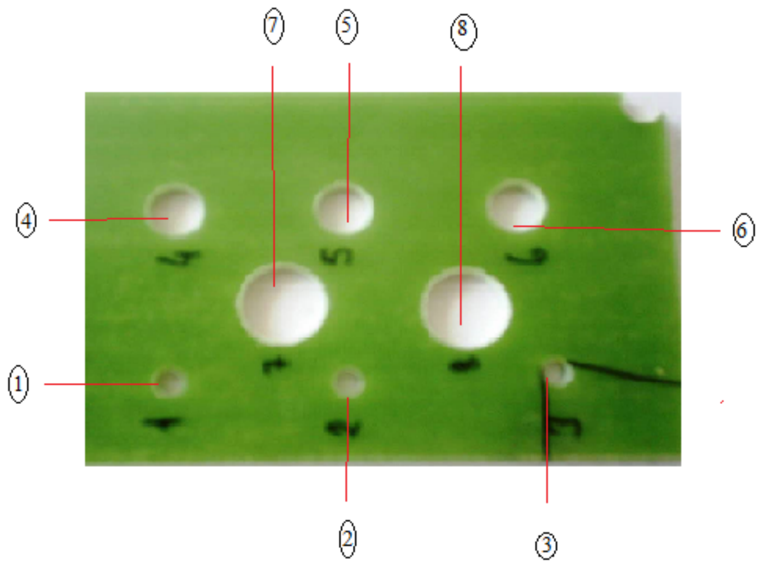

Figure 18. ISOVAL11 Composite materials used in experiments

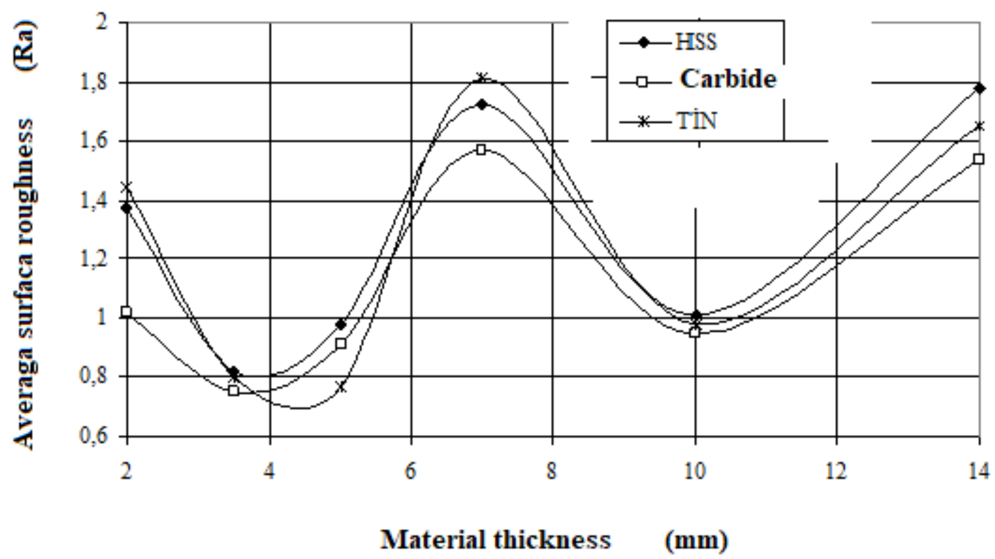

Figure 19. The change in material thickness and the average surface roughness for ISOVAL11 Epoxy/E-glass fiber composite (s=0.056 mm/rev, n=125 rpm, d=5 mm)

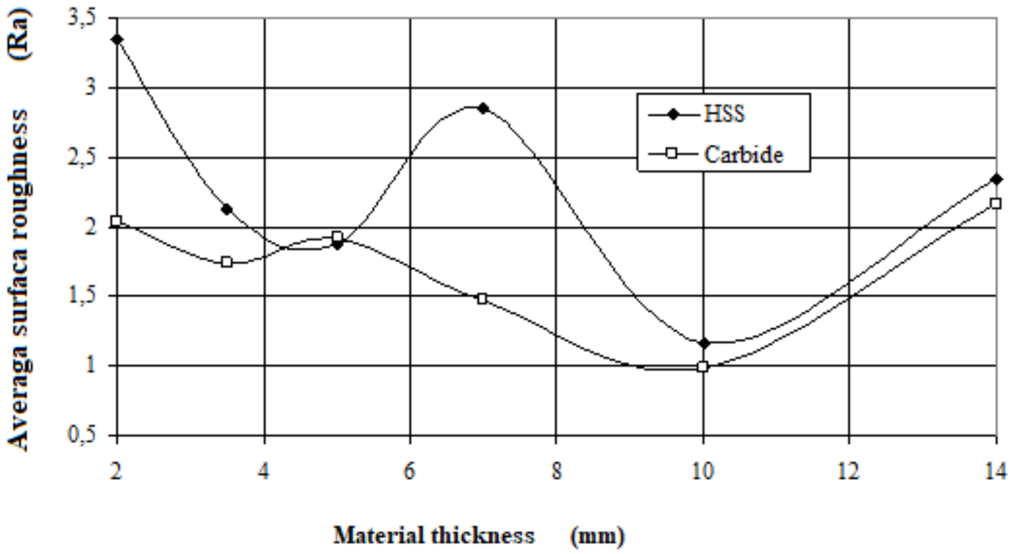

Figure 20. The change in material thickness and the average surface roughness for ISOVAL11 Epoxy/E-glass fiber composite (s=0.056 mm/rev, n=315 rpm, d=15 mm)

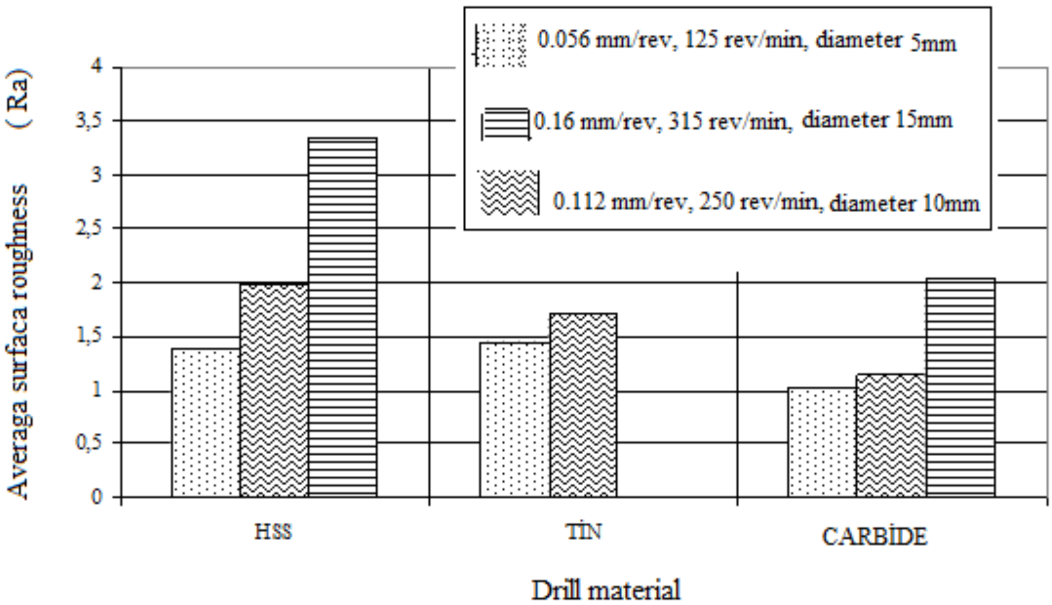

Figure 21. The change in drill material and the average surface roughness for ISOVAL 11 Epoxy/E-glass fiber composite (texture density =0.2 g/m^3, composite material thickness 2mm)

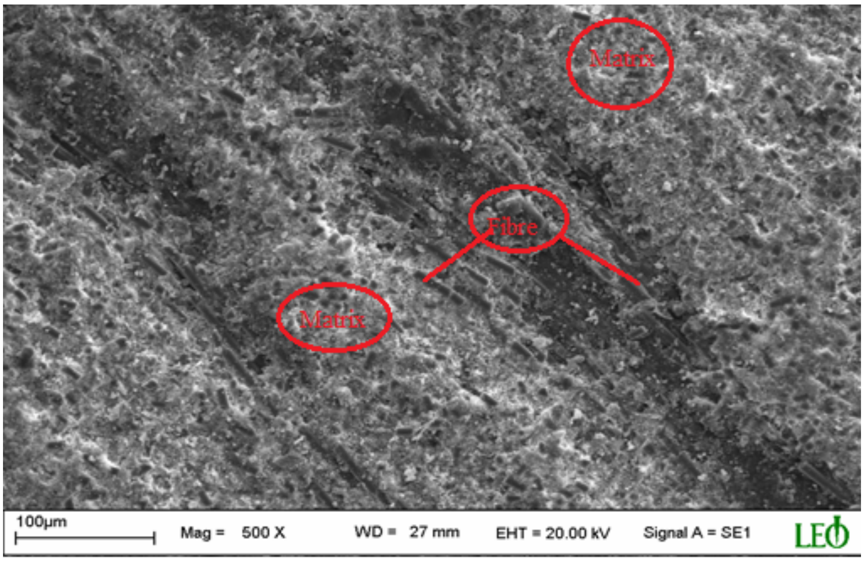

Figure 22. 500x enlarged SEM photo of middle point of hole section for ISOVAL11 Epoxy/ E-glass fiber composite drilled with HSS drill (texture density=0.2 g/m^3, composite material thickness =5, mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

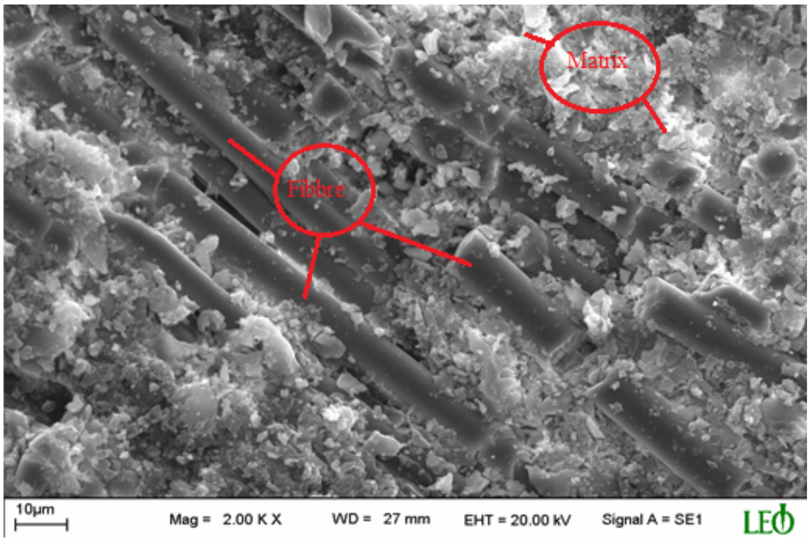

Figure 23 . 2000x enlarged SEM photo of middle point of hole section for ISOVAL11 Epoxy/ E-glass fiber composite drilled with HSS drill (texture density=0.2 g/m^3, composite material thickness =5, mm, s=0.16 mm/rev, n=315 rpm, d=15 mm)

5. Test Results and Discussion

In the present study, the surface roughness of the composite materials is examined depending on the effect of drill type, diameter of the drill, rotational speed, and feed rate regarding the machinability of various composite materials in the drilling process. Below-mentioned results are obtained as a result of the test studies:

- Since the coolant is not used, it caused the softening of the matrix material as a result of the heating around the hole. In all the drilling operations conducted by using drills, matrix condensation occurred on the surface edges of the holes.
- With the increase in the feed rate, sudden ruptures occurred between the lattices in the composite material and it is found that the values of surface roughness increased in the study.
- When the surface roughness values depending on the rotation speed are considered, it is observed that the surface roughness values increased as the speed increased in all the drilling processes conducted by using all types of drills.
- In general, it is observed that the surface roughness increased as the thickness of the material increased, and drilling became difficult, and the tool heating increased.
- Due to the increase of the shearing surface in contact with the material surface, it will cause an enlargement of the cutting area and thus create larger chips during drilling and will also increase the surface roughness. It is observed that the best results for all the drill types are obtained with the drills having small diameters and thus, the surface roughness increased as the drill diameter increased. This situation also gave the same results for CYCOM7714 and ISOVAL11 materials.
- Generally it is seen that, the biggest Ra value is obtained in HSS drill materials. During drilling of the materials extreme levels of heat were generated on the drill. Both ends of the segment are torn while they are drilled. As the material gets ruptured a hole is formed at that point. However, surface roughness is lower in middle layer, and especially Ra values are found to be much lower than fiber glass reinforcement.
- When an examination is performed among the materials, it is seen that the rupture strength of Kevlar reinforced material is higher than the fiber glass material, so it is more difficult to drill the Kevlar reinforced materials.

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